NETWORKED MULTI-AREA POWER SYSTEM: AN NON-FRAGILE CONTROL APPROACH

Research Protocol

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ABSTRACT:

this research proposes a non-fragile control approach for frequency restoration in networked multi-area power systems. the non-fragile control approach aims to design a controller that can tolerate uncertainties and disturbances in the system without compromising its stability and performance.

it is difficult to accurately model the power system because of uncertainties caused by modeling error, parameter change, and external perturbation.

similarly, designing a precise controller in a practical power systems are impossible due to environmental temperature drift, aging of power elements, coupling impact of modifying parameters, and so on.

actually, minor changes in model parameters and controller gain can cause power system instability, therefore model uncertainties and fluctuations in control gain must be considered.

Introduction

Load frequency control (LFC) is an essential aspect of active power and frequency control in power systems. Voltage and frequency deviations can occur due to various factors, including oscillations, generation mismatches, unexpected events, and uncertainties. These deviations can lead to equipment damage, degraded load performance, and overloaded transmission lines, ultimately resulting in unstable conditions in the power system.

The main goal of LFC is to maintain zero steady-state errors in frequency deviation and effectively track load demands. This objective has led to extensive research on LFC design to achieve satisfactory control system performance. Numerous LFC schemes have been proposed in recent years for different types of power systems, such as electric vehicles (EVs), smart grid systems, multi-area thermal systems, and wind farms. EV-based power systems have attracted significant attention due to their environmentally friendly characteristics, such as reduced greenhouse emissions and noise pollution.

In EV-based power systems, EVs can assist conventional power units in responding rapidly to system disturbances and meeting LFC requirements. Through bidirectional power electronic devices and vehicle-to-grid technology, an aggregation of EVs acts as a power source to support power units. EVs participate in LFC by helping suppress variations in system disturbances. Controller design for LFC often relies on a linear model obtained by linearizing around an operating point. However, power systems contain nonlinear components, which necessitates the adoption of linearized models in controller design.

In contrast, real-time processes face challenges in obtaining exact controllers due to unavoidable uncertainties in component aging, parameter readjustments, and network environment circumstances. These uncertainties can lead to small perturbations in control coefficients, potentially destabilizing the systems. Therefore, it is crucial to account for gain fluctuations during controller design. Non-fragile control approaches have been developed to tackle these issues, aiming to ensure stability in the considered systems.

Related Works

The LFC in power systems is not new to research community. The LFC problem in power systems have been tackled by various researchers and can be referred from the state of-the-art review in [1-4]. In general, the LFC comprises of two different control actions: the primary speed control and the supplementary speed control. The primary speed control performs the initial readjustment of the frequency and seems to be insufficient. Therefore, a supplementary speed control is added to the governor by means of signal directly proportional to the frequency deviation plus its integral action. This proportional plus integral control scheme constitutes the classical approach to the automatic generation control (AGC) of power systems. In complex scenarios, a classical control approach may not be enough to control sudden random variations in load.

Therefore, many other control methodologies/techniques such as optimal control approach, soft computing techniques, adaptive and self-tuning control approaches, robust control techniques, variable structure control etc. have already been investigated in the past. In the sequence, different control approaches reported so far in this field are briefly described.

1.2.1 Classical control techniques

Classical control approach mainly comprises of a fixed gain controller such as integral, proportional-integral (PI) and proportional-integral-derivative (PID). The major limitation of these controllers is that the dynamic performance of the controller is highly dependent on the selection of their gains. The pioneering work by famous control engineers namely, Nyquist, and Bode, established a link between the frequency response of a control system and its closed loop transient

performance. However, the usage of classical controllers revealed that the response was affected by large overshoots and transient frequency deviations as discussed in [5][6]. Also, the fixed gain controllers such as PI controller were adequate under designed conditions but not under other operating conditions. Few classical control techniques using root loci, Nicholas plot, Ziegler Nicholas tuning method for a PID based load frequency controller is discussed in [7-9].

1.2.2 Optimal control techniques

Optimal control techniques deal in finding a control input over a period of time such that an objective function (cost) is minimized. Minimization of this cost yields an optimal controller that is a linear combination of system states. These methods result in improved dynamic response and wider stability margin. A new feedback control law for two area non-reheat type thermal power system using state variable and a regulator problem of optimal control theory is proposed in [10]. A PI type optimal regulator solution for load and frequency control in an interconnected power system is reported in [11]. The effect of plant response time on the closed loop poles of the LFC system designed using optimum control theory is investigated in [12]. In the context of optimal decentralized LFC for multi area interconnected power systems, a fixed mode evaluation algorithm based on eigen value dynamics is reported in [13].

1.2.3 Soft computing control techniques

As far as the design of any controller is concerned, its parameters play a pivotal role in the overall performance of the closed loop system. Therefore, controller gains should be tuned properly with proper optimization techniques. Soft computing techniques such as artificial neural network (ANN) [14][15], fuzzy logic [16][17], genetic algorithm (GA) [18][19], artificial neuro-

fuzzy inference system (ANFIS) trained using particle swarm optimization (PSO) [20], bacteria forging [21], big bang big crunch (BBBC) [22], ant colony optimization [23], fruit fly optimization algorithm [24] etc. have been reported several times in the literature.

1.2.4 Adaptive and Self-tuning control techniques

The controller performance may not be optimal if the operating condition of the system keeps on changing. In order to maintain the system performance near to optimal value, it is desirable to track the operating point of the system and accordingly update the controller parameters. Adaptive and self-tuning control approaches answer the above problem. Several adaptive and self-tuning control approaches for load frequency problems in power systems where the controller gains are adaptively tuned are reported in [25-30]. These techniques eliminate the problem of overestimation of controller gains.

1.2.5 Robust control techniques

A conventional LFC is often incapable of providing good dynamical performance for wide range of operating condition and various load scenarios. Thus, various robust control techniques namely, Riccati equation based approach [31], H_∞ [32-34], H_2 / H_1 [35], μ - synthesis approach [36][37] based on linear matrix inequality (LMI), LMI based PID controller [38] have been adopted to tackle the load frequency problems under varying operating conditions and load scenarios.

1.2.6 Variable structure control (VSC) techniques

The VSC is a well-known nonlinear control strategy to improve the dynamic performance of the system. This control method alters the dynamics of the nonlinear system by application of

high frequency switching control. The SMC is a well-known VSC with inherent advantages like robustness, faster convergence, insensitivity to disturbance and uncertainties etc. In order to improve the system performance, the VSC applied to a problem of AGC in an interconnected power system is discussed in [39][40]. A decentralized SMC for load frequency problems in an interconnected power network is proposed in [41-44]. It should be noted that design of any state feedback controller requires information about all the system states. However, not all the system states are available or are measurable. In such case, system states are estimated using a process known as "*observation*". An observer-based nonlinear control of power system using the SMC strategy is reported in [45]. The SMC techniques based on disturbance estimation is reported in [46][47]. A disturbance observer (DO) firstly estimates the exact mismatch between the total generation and the total load demand and then the obtained information is used in the controller design.

1.2.7 Robust control techniques with time delays

Multi area interconnected power systems are classical example of a networked control system (NCS). A NCS is a system in which communication between the different components like controller, sensor and actuators are possible using communication links rather than point to point wiring. A NCS is often affected by time delays. Time delays can be transport, communication, measurement delay or even natural. Furthermore, time delays can also be injected in the system from outside. A small amount of time delay can destabilize the system or deteriorate the controller performance. Therefore, stability of systems with time delays has to be given a lot of attention. Time delays in power system can be present in sensing loop or control loop or both. In the context of the LFC in power systems with time delays, significant number of works has been reported so

far as in [48-50]. The LFC of two area power system under time delay switch attacks (TDS) is discussed in [51][52]. Sliding mode observer (SMO) based LFC of multi area power systems under delayed input attack is reported in [53]. Furthermore, a delay-dependent stability of the LFC scheme by using Lyapunov-theory based delay-dependent criterion and LMIs techniques is investigated in [54]. To achieve fewer conservative results, an improved delay dependent condition in terms of LMIs for single-area and multi-area LFC systems deduced by augmented Lyapunov-Krasovskii functional is proposed in [55].

1.2.8 Event triggered control (ETC) techniques

Large scale interconnected power systems are systems often characterized with heavy transmission burden and small communication times. Therefore, it is desirable to reduce the communication burden between the sensors and controller nodes. Maximizing the time intervals that the nodes need to send data to each other is an effective way. Furthermore, to reduce the control costs, the LFC scheme is often embedded with micro-processors which are usually run with limited energy resources and computing capability. This inspired the researchers to establish the ETC scheme over digital-operating platforms for the LFC. In this control technique, the control input is not updated in periodic manner as it is usually done in the classical sampled data system [56]. In the context of communication time delays, an event triggered and an adaptive event triggered LFC for multi area power system is discussed in [57-61].

1.2.9 Active disturbance rejection control (ADRC) techniques

The central idea of an ADRC is to treat the internal uncertainties and external disturbances as a generalized disturbance. And further, try to estimate it in real time by an extended state

observer (ESO), and then use it in the feedback with the aim to compensate the disturbance quickly. This technique was first proposed by Prof. Han. Significant works have been reported using ADRC in the field of the LFC in power systems and can be referred from [62-64].

1.2.10 Non-fragile control approach

In [65], Ji et. al. (2023) investigates the problem of fault-tolerant load frequency control for multi-area power systems with actuator failures, focusing on non-fragile H∞ control. To model actuator partial failures, a stochastic distribution model is established, taking into account the distribution characteristics. In order to design a fault-tolerant controller that can handle both additive and multiplicative uncertainties in controller gains, a novel approach is proposed. The previously challenging coupling items are reformulated as a W-problem in fault-tolerant load frequency control. Additionally, a new algorithm is developed using linear matrix inequalities technology and the Lyapunov-Krasovskii functional method, which is tailored to the specific failure distribution.

In [66], Qiao et. al. (2023) introduces a new approach called non-fragile output sliding mode load frequency control (OSMLFC) for multi-area interconnected power systems with electric vehicles (EVs), specifically focusing on mitigating frequency-triggered denial-of-service (DoS) attacks. The security of network communications in load frequency control (LFC) power systems with EVs, studying the impact of real-time frequency-triggered DoS attacks by combining

frequency dynamics with event-triggering mechanisms. A non-fragile output sliding mode control (SMC) technique designed to effectively manage load and frequency in power systems.

In [67], Zhou et. al. (2023) proposes a new approach to load frequency control (LFC) in wind power systems. The approach is based on a discrete proportional-integral-derivative (PID) scheme and utilizes a non-fragile design approach to investigate dissipative analysis issues. The article begins by constructing a unified model for interconnected power systems with multiple governors, taking into consideration the different power-sharing rates of the governors. Unlike existing LFC schemes, the proposed approach utilizes a non-fragile discrete PID control scheme. This scheme is designed to tolerate control gain fluctuations and alleviate the computational burden associated with LFC. To establish improved stability criteria with a strict dissipative performance index, the article constructs a discrete-type Lyapunov-Krasovskii functional.

In [68], Zhong et. al. (2021) introduces a new approach for load frequency control (LFC) in multi-area nonlinear power systems (NPSs) using a dynamic triggered algorithm (DTA) and a non-fragile proportional integral control (NPI-control) strategy. A nonlinear multi-area model is constructed that takes into account overshoots and long-term oscillations, which are not considered in existing linear single-area LFC models. The NPI-control scheme is applied to the LFC approach for NPSs for the first time, considering control uncertainty. The DTA adjusts the dynamic event-triggered parameters, reducing communication bandwidth and data computation. A novel relaxed Lyapunov-Krasovskii functional is constructed using a modified quadratic form with a time-varying matrix, resulting in less conservatism in the stability criteria.

In [69], Azarbahram et. al. (2019) introduces a new method for load frequency control (LFC) in multi-area power systems. The proposed method utilizes an integral-based non-fragile

distributed fixed-order dynamic output feedback (DOF) tracking-regulator control scheme. The model used to represent the power systems includes uncertainties and time-varying communication delays. The design process involves formulating the problem as a semi-definite programming and linear matrix inequality (LMI) optimization problem. By solving the proposed LMIs, the necessary parameters for the tracking controllers are obtained, ensuring minimal impact from model uncertainty and load disturbances. The controllers are capable of receiving information from all or some of the subsystems, while their outputs remain local. These controllers are designed to guarantee resilient stability of the overall closed-loop system.

In [70], Anand et. al. (2021) a non-fragile load frequency control scheme is proposed to address the challenges of a multi-area power system that includes an energy storage system and wind power. A dynamic model is developed for this system, considering time delays and uncertainties while satisfying circular pole constraints. Additionally, a non-fragile control approach is employed to ensure that the closed-loop poles of the discretized model fall within a specified circular region inside the unit disk.

In [70], Zhang et al. (2018) focus on non-fragile filtering in large-scale power systems with sensor networks. The objective is to estimate the state of each subsystem and transmit these states to various locations. To achieve this, the researchers derive sufficient conditions that guarantee the asymptotic stability of the filtering error system with a desired level of performance, using the robust control approach. The parameters of the filter are determined by solving a set of linear matrix inequalities.

In [71], Aravindh et. al. (2018) focuses on the problem of designing reliable load frequency control for an uncertain multi-area power system with constant time delays and disturbances. The

approach used is a non-fragile sampled-data control approach. The parameter uncertainties in the system are assumed to occur randomly and are described by Bernoulli distributed sequences. The paper proposes a new set of conditions, expressed in terms of linear matrix inequalities, that ensure the asymptotic stability and extended dissipativity of the multi-area power system. These conditions hold not only when all actuators are functioning, but also in the case of some actuator failures. Simulation results are provided to demonstrate the effectiveness of the proposed control design technique.

Problem Definition

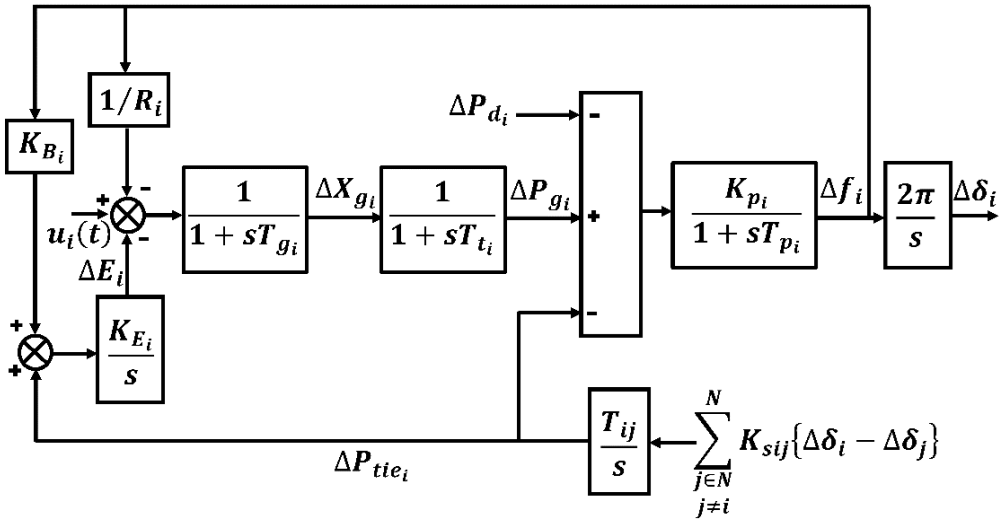

Figure 1: Interconnected load frequency control model [10].

Traditionally, power systems have been described as being extremely complex, dynamic, and nonlinear. It is possible to employ a linearized model in the LFC problems since only minor changes in load may be predicted during the course of its regular operation. In order to create the state variable model, one must first define the state equations as follows,

$$\Delta \dot{f}_i(t) = -\frac{1}{T_{p_i}}\Delta f_i(t) + \frac{K_{p_i}}{T_{p_i}}\Delta P_{g_i}(t) - \frac{K_{p_i}}{T_{p_i}}\Delta P_{d_i}(t) - \frac{K_{p_i}}{2\pi T_{p_i}}\sum_{\substack{j\in N \\ j\neq i}}^{N} K_{sij}\left\{\Delta\delta_i(t) - \Delta\delta_j(t)\right\} \quad (1)$$

$$\Delta \dot{P}_{g_i}(t) = -\frac{1}{T_{t_i}}\Delta P_{g_i}(t) + \frac{1}{T_{t_i}}\Delta X_{g_i}(t) \quad (2)$$

$$\Delta \dot{X}_{g_i}(t) = -\frac{1}{R_i T_{g_i}}\Delta f_i(t) - \frac{1}{T_{g_i}}\Delta X_{g_i}(t) - \frac{1}{T_{g_i}}\Delta E_i(t) + \frac{1}{T_{g_i}}u_i(t) \quad (3)$$

$$\Delta \dot{E}_i(t) = K_{E_i}\left[K_{B_i}\Delta f_i(t) + \frac{1}{2\pi}\sum_{\substack{j\in N \\ j\neq i}}^{N} K_{sij}\left\{\Delta\delta_i(t) - \Delta\delta_j(t)\right\}\right] \quad (4)$$

$$\Delta\dot{\delta}_i(t) = 2\pi\Delta f_i(t) \tag{5}$$

Rewriting equations (1)-(5) in matrix form,

$$\dot{x}_i(t) = A_i x_i(t) + B_i u_i(t) + \sum_{\substack{j\in N \\ j\neq i}}^{N} E_{ij} x_j(t) + F_i \Delta P_{d_i}(t) \tag{6}$$

The state vector and the matrices are represented as follows,

$$x_i(t) = \begin{bmatrix} \Delta f_i(t) & \Delta P_{g_i}(t) & \Delta X_{g_i}(t) & \Delta E_i(t) & \Delta\delta_i(t) \end{bmatrix}^T \tag{7}$$

$$A_i = \begin{bmatrix} -\frac{1}{T_{P_i}} & \frac{K_{P_i}}{T_{P_i}} & 0 & 0 & \frac{-K_{P_i}}{2\pi T_{P_i}} \sum_{\substack{j\in N \\ j\neq i}}^{N} K_{sij} \\ 0 & -\frac{1}{T_{T_i}} & \frac{1}{T_{T_i}} & 0 & 0 \\ -\frac{1}{R_i T_{G_i}} & 0 & -\frac{1}{T_{G_i}} & -\frac{1}{T_{G_i}} & 0 \\ K_{E_i} K_{B_i} & 0 & 0 & 0 & \frac{K_{E_i}}{2\pi} \sum_{\substack{j\in N \\ j\neq i}}^{N} K_{sij} \\ 2\pi & 0 & 0 & 0 & 0 \end{bmatrix} \tag{8}$$

$$B_i = \begin{bmatrix} 0 & 0 & \frac{1}{T_{G_i}} & 0 & 0 \end{bmatrix}^T \quad C_i = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{9}$$

$$F_i = \begin{bmatrix} -\frac{K_{P_i}}{T_{P_i}} & 0 & 0 & 0 & 0 \end{bmatrix}^T \tag{10}$$

$$E_{ij} = \begin{bmatrix} 0 & 0 & 0 & 0 & \dfrac{K_{P_i}}{2\pi T_{P_i}} K_{sij} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\dfrac{K_{E_i}}{2\pi} K_{sij} \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{11}$$

Methodology

An implicit assumption is that the controller shall be implemented exactly as designed. This is a valid assumption because plant uncertainty is the major source of uncertainty in the control system, and controllers are constructed with high precision hardware. However, there will always be some uncertainty in the controller gain design: if the controller is implemented in analog circuits, there will be some tolerances in the analog components; if the controller is implemented digitally, there will be uncertainty in the quantization in the analog-digital conversion and rounding in the parameter representation and numerical computations. In actuality, any controller must be able to tolerate some uncertainty in its coefficients due to the imprecision of controller implementation or the necessity for readjustment of its coefficients. It's very interesting and challenging to combine the load frequency control with non-fragile based control approach.

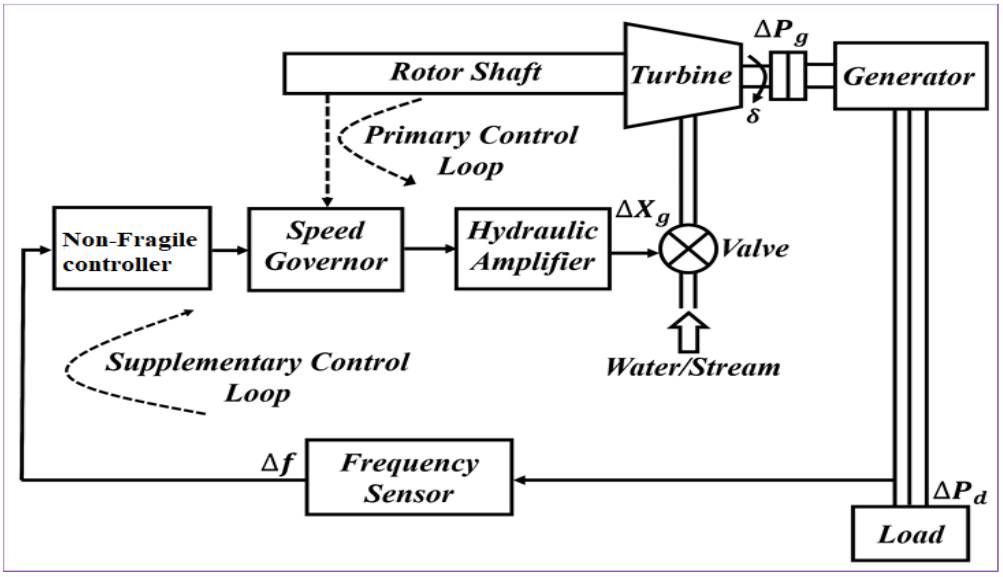

Figure 2: Proposed Load frequency control model with non-fragile control

Research Objectives:

- To identify the research gaps and challenges in frequency restoration of networked multi-area power system based on non-fragile control.
- To develop a control approach which can withstand the fluctuation in controller gain parameters ensuring system stabilizations.
- To design the disturbance attenuation technique along with non-fragile control mechanism which can mitigate the effect of wind disturbance (ensuring stability of power system with integration of wind energy).

Expected outcome

- The proposed non-fragile control with ensure the stability of the networked multi-area power system with uncertainties in the controller gain parameters.
- The combination of disturbance attenuations control approach is combined with the non-fragile control approach with exhibit the properties of both ensuring the stabilization of system also.
- The proposed controller is also verified with the integration of renewable energy sources.
- The superiority of the proposed control will be also shown by comparing with the recent works.

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